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Research paper

Low-ILUC-risk ethanol from Hungarian maize

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ABSTRACT

Indirect land use change (ILUC) is a serious threat to the sustainability of bioenergy because of the extra GHG emissions (and other environmental impacts) it causes when feedstock production diverts other agricultural production and causes expansion onto high carbon stock lands. However, multiple measures exist to reduce the risk of ILUC. But these measures and their potential to mitigate ILUC are not yet well understood. Therefore, we assessed the ILUC-mitigation potential under three scenarios for possible developments in agricultural production and supply chains for a case study on maize production in Hungary for ethanol. Our results show that ILUC-risk mitigation is possible in all three scenarios: agricultural land demand is reduced by 3500–16000 km^2 in 2020 compared to the current situation (6–29% of the agricultural area). This surplus land, is not needed anymore for food and feed production and can be used for biomass production for energy at a low risk of causing ILUC. For example, when maize is cultivated and converted to ethanol, this surplus land can provide 22-138 PJ of ethanol. This is equivalent to 10–60% of the projected 2020 transport energy use in Hungary. Yield improvements of maize, other crops and livestock contributed most (55–90%) to this low-ILUC-risk potential. To sustainably increase productivity and efficiency in the entire agricultural sector, an integrated approach to food and fuel (as well as other non-food) production is needed. Thereby, ILUC risk can be mitigated and is not an irreversible fact as often presented in previous studies.

1. Introduction

Indirect land use change (ILUC) induced by increased biofuel production is a widely discussed topic in academia and the policy arena. ILUC occurs when a growth in biofuel feedstock production in a region leads to displacement of agricultural production to other regions [1–4]. This displacement can trigger deforestation or other large carbon stock changes, which reduce or even cancel out the beneficial greenhouse gas (GHG) emission effects of biofuels [1].

Due to the indirect nature of the effect, it is not possible to classify specific land use change as an indirect effect of biofuel expansion. Rather, all land use changes will have a complex mix of multiple drivers that steer them. Therefore, models are used to project direct and indirect land use changes (LUC) induced by additional biofuel demand and the resulting emissions [5]. Most studies about ILUC use global macro-economic models to assess the effects of an increase in biofuel production on the economy, which is then translated into a land-use change effect by comparing a business-as-usual scenario without extra biofuel use, to a scenario with additional biofuel use [1,6–10].

The results of these studies show largely different impacts of ILUC, but the projected CO_2 emissions from LUC are always above zero [11,12]. Despite the uncertainties about the precise impact, this indicates that the risk of ILUC needs to be tackled. A policy measure that is often proposed to limit the extent of ILUC emissions is an ILUC emission penalty, which has to be added to the GHG balance of the biofuel product [13]. Since biofuels have to meet criteria for GHG emission savings compared to reference fossil fuels (e.g. −35% now; −50% from 2016 onwards in the EU Renewable Energy Directive [14]), this policy would make it more difficult for biofuels, and in some supply chains impossible, to achieve these savings.

While such a LUC penalty is already implemented in California [8], the EU chose not to do so now in the 'ILUC directive' of 2015 after intensive negotiations between members states, commission and parliament [15]. The criticism on the use of an ILUC penalty is threefold. Firstly, the proposed penalties are based on the outcome of macro-economic models, which are associated with large uncertainties [12,16–18]. This results in a penalty that does not reflect

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Abbreviations

CAP	Common Agricultural Policy
CEE(C)	Central and Eastern European (Countries)
DDGS	Dried Distiller Grains and Solubles
EU27	European Union before Croatia joined
FAO	Food and Agriculture Organisation
GAEZ	Global Agro-Ecological Zones
GHG	Greenhouse Gas
HHV	Higher Heating Value
ILUC	Indirect Land Use Change
LCA	Life Cycle Assessment
LUC	Land Use Change
MIRAGE-BioF	Modeling International Relationships in Applied General Equilibrium for Biofuel
NLU	National Livestock Units
NREAP	National Renewable Energy Action Plan

the actual impact of the biofuel, but rather a value choice. This problem is enhanced by the fact that some of the models are not open to public scrutiny. Secondly, it imposes a uniform penalty on each feedstock, irrespective of where and how it was produced. It thereby disregards that some regions or companies try to mitigate the ILUC risk e.g. by using otherwise under-utilised land or increasing yields. Thirdly, the ILUC penalty approach also disregards the fact that all ILUC caused by biofuels is also the direct land use change of other production. This means the problem is larger than just biofuels and requires a holistic approach to the agricultural sector as a whole.

Given these shortcomings of the ILUC penalty approach and limited attention for alternative approaches so far [11,19,20] as well as the decision of the EU's ILUC directive to focus on ILUC mitigation [15], this study aims to assess and quantify the extent to the risk of indirect land use change can be mitigated. We explore the potential for low-ILUC-risk biofuels by assessing four ILUC mitigation measures for a case study on maize for ethanol in Hungary. Hungary is chosen as a case study because it is an important agricultural country, with a large production of maize. Moreover, it is a country in Central and Eastern Europe (CEE), where large future biomass supplies are projected [21–24]. Part of the potential in Hungary originates from the start of the 1990s, because after the end of the communist era the demand from Russia for meat and thereby also for intermediate products collapsed. This resulted in lower land demand and lower productivity and thus a larger yield gap [25,26].

2. Methods and materials

2.1. General approach

The approach applied here was developed by Brinkman et al. [27], and was applied by Gerssen-Gondelach et al. [28] and Van der Laan et al. [29]. It aims to analyse and quantify ILUC mitigation measures. We assess how much additional biofuel feedstock can be produced on surplus land (the biofuels from these surplus lands are hereafter also called the low-ILUC-risk potential) as a result of these measures. Surplus land is i) land that is included in current agricultural land use, but that is not required anymore for food, feed or fibre production in 2020 as a result of the application of the ILUC mitigation measures, or ii) land that is currently not in use, but has low carbon stocks. The approach to calculate the amount of surplus land is based on a combination of a top-down and a bottom-up assessment, and it distinguishes three main steps that are summarised in Fig. 1 and described below.

The total land use change that is caused by biofuel expansion (direct and indirect) can be measured by calculating the difference between the land use for food, feed, fibre and current amount of biofuels in a baseline (or business-as-usual scenario) and a biomass target scenario that includes additional demand for biofuels. The additional biofuel production that is projected (step 1) can lead to a expansion of agricultural land elsewhere (section 2.2). Then we assess the potential of four different measures (section 2.3) to make more land available for biofuel feedstock (step 2), without the need for diversion of production to other regions. We do this for three different scenarios (see section 2.3.1). The comparison (step 3) between the top-down demand and bottom-up supply shows to what extent we can mitigate LUC with the four measures.

2.2. Step 1 agricultural production in 2020 prescribed by top-down model

In the first step, we used the outcomes of the MIRAGE economic model to establish top-down a crop-specific biomass production baseline (without additional biofuels) for 2020 [9]. MIRAGE (Modeling International Relationships in Applied General Equilibrium) is a computable general equilibrium model from the International Food Policy Research Institute (IFPRI). The version used here is MIRAGE-Biof which was used for 2011 study for the DG Trade of the European Commission and was the basis for the ILUC penalties proposed by the EC [9]. Based on changes in demand for agricultural products resulting from development in macro-economic conditions (e.g. economic and population growth, trade policies), the model projects the production quantities in 2020. We applied the results specific to the "status quo" trade policy projection of the MIRAGE model.

The MIRAGE crop production data for the EU27 were disaggregated to Hungary by taking the current share of Hungary in the EU-wide production of each crop [30]. For this, we used the ten most important crops (by land use) in Hungary today, of which six matched the crop categories of the MIRAGE model. The crops that were not included as a separate category in the MIRAGE model were included under *other crops*, and the disaggregation within that category was again based on the current share of the production of that crop within that category. For the production data, we used a five year average (2008–2012) to account for the yearly variations in production caused by weather. The crop production volumes were converted to the land use for the production, using the MIRAGE-projected yield of each crop. For the current yield, data from FAOSTAT [30] and the Hungarian Central Statistics Office [31] were used. As the MIRAGE model aggregated the EU27 countries into one region, with one yield for each crop, there is no distinction in the yield development between the countries. In order to avoid complicated disaggregation methods, we assumed for the yield in 2020 the growth percentage in Hungary will be the same as projected for the whole EU27. These crop productions and yield projections are presented in Table 1 alongside the other land uses in Hungary in 2010, based on FAOSTAT data [30].

2.3. Step 2 bottom-up assessment of the measures

In the second step, a bottom-up approach was used to assess the biomass production potential from key ILUC mitigation measures (Section 2.3.2–2.3.5). A baseline and three scenarios -*low*, *medium* and *high* progress-are applied in order to indicate the variability and uncertainty in the developments in the agricultural sector (Section 2.3.1).

2.3.1. Scenarios

Three scenarios are applied to illustrate different routes along which implementation of the ILUC mitigation measures may take place and to reflect the varying extent to which ILUC mitigation measures may be implemented and the speed of progress in the Hungarian agricultural sector. In addition, the use of scenarios helps to identify the ranges for the low-ILUC-risk potential. In order to contrast and compare the effect of these scenarios, also a baseline scenario was needed. Below we shortly describe the general blueprint in which the scenarios fit; Table 2 gives an exact overview of the assumptions per measure of the three scenarios and the baseline Table 3 and [32] give a more elaborate overview of the precise numbers for each scenario.

The *baseline* scenario was based on the reference assumptions of the MIRAGE model (see also section 2.2), which was also used in the past to assess the extent of ILUC and its associated GHG emissions [9]. The reference scenario included changes in demand for food, feed and fibre, but not for biofuels. Also the trade policy was assumed not to change. As current agricultural policies in Hungary are not focussed on increasing the efficient use of agricultural land, only little progress is assumed in the *low* scenario. In view of the current political situation, the stance to favour smallholders over productivity gains was not expected to change in the coming years. The assumption behind the *medium* scenario is that there is a potential within the country to learn from other regions in the country or from the past, if better results were achieved then. It is likely that previous performances can be matched in the present, or that some regions can achieve the current best as Hungary is a relatively small and agriculturally homogenous country, with few regional differences. The *high* scenario is the upper bound of the development and assumes fast progress. We assumed for the *high* scenario that the country can reach the level of the rest of the EU, as it has joined the EU and the Common Agricultural Policy in 2004.

2.3.2. Above baseline yield increase

The first measure is above baseline yield improvement. The *baseline* projections for the yield growth are presented in Table 1. Maize and wheat yield growth are 2.6% and 2.1% respectively, over the entire 2008–2020 period [9]. This is a low increase, and current yield in other European countries and past experience show a higher yield increase could be feasible, even over multiple years. A historical comparison of yield developments of key crops and livestock products produced in Western and Central and Eastern Europe (CEE) by De Wit et al. [22] showed that between 1961 and 2007 the annual yield growth rates averaged over ten year periods ranged between −1% and 6%, with the largest yield increases in CEE. The feasibility is further illustrated by the fact that between 1967 and 1981 yearly maize yield growth in Hungary did not fall below 3.1% [30]. Furthermore, the yield gap in those days was significantly smaller than today. Analyses by Gerssen-Gondelach et al. [33] showed yields grow faster in areas with a higher yield gap. Maize yields in Hungary were almost 70% of the highest maize yields in the world in the 1970s; now it is only 23% of the current best [30]. An additional reason to assume higher yield increases are achievable is that the main cause of the low yield is not biophysical, but related to management. Implementing better management practices can lead to a rapid increase in crop yield. Currently, agricultural management practices in Hungary lag behind those in Western Europe, with low mechanisation, fertiliser and pesticide use [25,30,34]. Optimising fertiliser use can improve production and thereby decrease GHG emissions per unit of crop. However, at the moment farmers often lack capital, knowledge and incentives to invest in agricultural productivity. Therefore, policies to improve the yield need to stimulate and provide incentives these investments in order to improve mechanisation and proper use of fertilisers and pesticides. Thereby, performance of the agricultural sector as a whole can be increased and GHG emission savings from biofuels raised. For maize this is illustrated in Fig. 2. Because higher yielding crops require less land for the same production, land demand decreases and the surplus area increases. Equation (1) calculates for each crop the amount of land that is required to produce the desired crop production volume in 2020 with the baseline yield development and a yield defined in the scenarios:

$$SA_{\mathrm{ABY,crops}} = \mathrm{A_{baseline}} - \mathrm{A_{ABY}} = \sum_{i=1}^{n} \frac{P_{\mathrm{i}}}{Y_{\mathrm{baseline,i}}} - \sum_{i=1}^{n} \frac{P_1}{\mathrm{Y_{ABY,i}}} \quad (1)$$

where

$SA_{\mathrm{ABY,\ crop}}$ – surplus area (ha) that becomes available from above-baseline yield increases (ABY) for crops;
A_{baseline} – area (ha) needed for projected target crop production, applying the MIRAGE yield growth rate;
A_{ABY} – area (ha) needed for projected crop production, applying an improved yield growth rate;
$Y_{\mathrm{baseline,i}}$ – projected baseline yield for crop i (t ha^{-1} y^{-1});
$Y_{\mathrm{ABY,i}}$ – projected above-baseline yield for crop i (t ha^{-1} y^{-1});
P – projected baseline production (tonne) for crop i, as derived from the MIRAGE model.

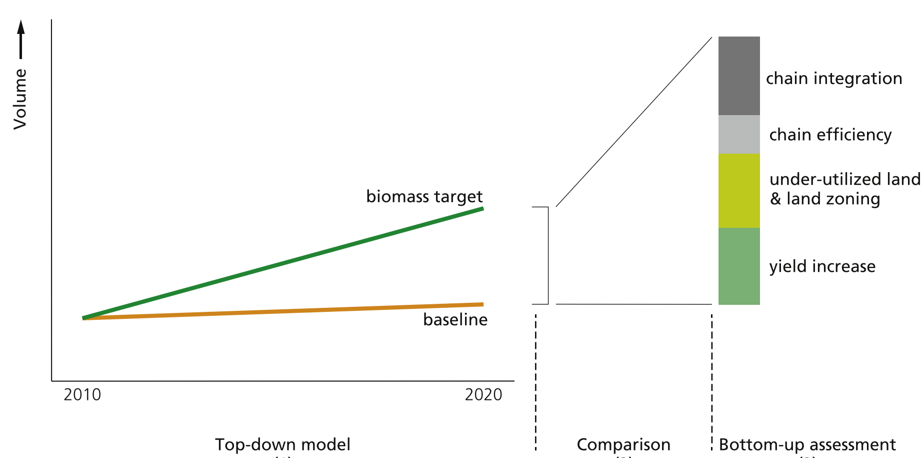

Fig. 1. Three steps to analyse the potential low-ILUC-risk biofuel potential of a region (from Brinkman et al. [27]).

Table 1
Overview of production, yields and land use in Hungary for the crops used in this study. Current production and yield data are taken from FAOSTAT, future production is disaggregated from MIRAGE EU27 data [9]. This production is for food, feed fibres and current amount of fuels. Forest area and meadows and pastures are taken from FAOSTAT [30].

Crop	Production 2010 (kt)	Production 2020 (kt)	Yield 2010 (t ha^{-1})	Yield 2020 (t ha^{-1})	Area 2010 (km^2)	Area 2020 (km^2)
Maize	7229	8190	6.2	6.3	11 700	13 000
Wheat	4328	4979	4.1	4.1	10 700	12 100
Sunflower seed	1277	1573	2.3	2.6	5600	6000
Barley	1092	694	3.7	3.8	2900	1820
Sugar beet	751	805	55	59	140	140
Potato	559	356	25	26	220	140
Rapeseed	541	736	2.3	2.5	2300	2900
Oats	136	87	2.5	2.6	540	340
Rye	83	53	2.2	2.3	380	230
Soybean	79	103	2.2	2.3	360	440
Total					34 900[a]	37 100
Meadows and pastures					8730	
Forest					20 400	

[a] The area of other crops combined is 4400 km^2.

For the surplus land as a result of intensification in the livestock sector only grazing cows and sheep are considered. Other studies (e.g. Refs. [22,33]) only considered cattle because it has the largest land-use impact. The land intensity of pigs and poultry are much lower, as these are mostly held inside [33]. Because of a large sheep flock of 1.2 million units in Hungary, compared to 0.7 million units of cattle [31], sheep were also considered here. As we focus on the reduction of land use change, we only consider grazing cattle and sheep. There was 8730 km^2 of meadows and pastures (see Table 1) available for the livestock. Two types of yield improvement were taken into consideration: i) productivity per animal, which reduces the number that has to be held, and ii) the heads per hectare. For cattle, we considered both meat and milk production and for sheep only wool production as the sheep milk and meat production is very low compared to that of cattle. In contrast to our projections of crop production, for livestock, we did not use results from the MIRAGE model. The MIRAGE model does not present livestock production in terms of physical units, instead, the value added of the cattle sector is presented. This is project by the MIRAGE model to grow by 4% (2008–2020), with a very slight change in prices (−0.2%). Based on these available data we were unable to discern the price effects from the volume effects [9]. An alternative approach for projecting changes in future production volumes in the livestock sector is to extrapolate FAOSTAT data of meat and milk production. While these data show some changes in Hungary over time, no definitive upward or downward trend could be discerned [30]. Therefore, we choose not to include a growth in production of meat, milk and wool in Hungary in the coming years.

For beef and milk productivity per cow, we used production data from FAOSTAT as these are data that can be compared to other countries and over time [30]. We considered the milk production per cow and the carcass weight per cow. It was assumed in all scenarios that a rise in productivity per animal would be matched by an equal reduction in the number of animals in such a way the total production of milk and beef would not change. The productivity increases per scenario are defined in Tables 2 and 3

For the increase in the heads per hectare a metric for the density was needed for the calculations. Therefore, we multiplied the amount of grazing cows and sheep by their respective National Livestock Unit equivalents [34]. The amounts of grazing cattle (27%) and sheep (67%) were calculated using the data from the Hungarian agricultural census of 2013 [34], the amount of animals was taken from FAOSTAT in order to make comparisons possible. These calculations implicitly assumed the grazing pattern would not change, however data collection is insufficient to assess this. The difference between the land use before the yield improvements and after the yield improvements is defined as the surplus land.

2.3.3. *Improved chain integration*

The second measure is improved chain integration. Co-products from feedstock cultivation and biofuel production can be used to replace other products, which decreases the demand for these. Co-products that are included in this analysis are distiller grains and solubles (DGS) that can be used as animal feed, and maize stover that can either be used for animal feed or second generation

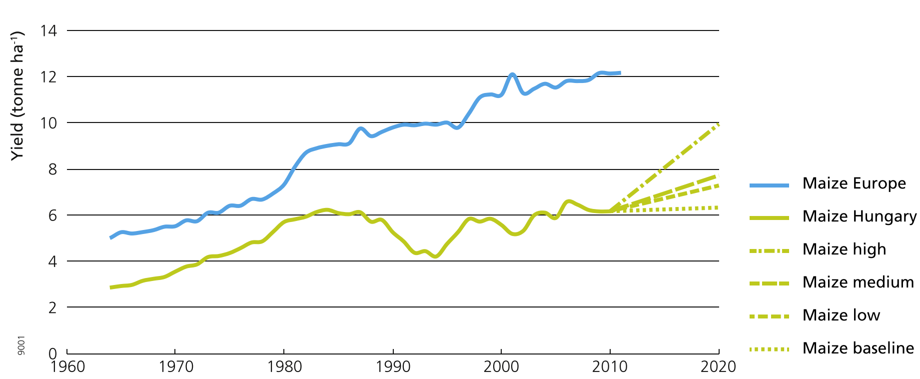

Fig. 2. Maize yield development in Hungary and Europe in the period 1964–2020. Data for the period up to 2010 is a five year moving average, from FAOSTAT data [30]. The yield growth in the period 2010–2020 is based on the *low*, *medium*, and *high* scenarios (section 2.3.1).

ethanol production. Because the MIRAGE model includes the use of DDGS as animal feed in its calculations an equal amount of agricultural production was added to the projected production in 2020 to avoid double counting (this is the only diversion from the baseline scenario as described in section 2.3.1). Although the MIRAGE model includes this effect already, we calculated it separately in order to be able to quantify the effect and assess how the key variables influence this. The additional DDGS production from MIRAGE was calculated using the co-production factor and the replacement rate of the co-products as defined in the study by Laborde [9], which in the case of maize DDGS are very high. The amount of maize allocated to ethanol production was based on the European average (2.2%) in the 2020 reference case of Laborde [9].

To calculate the land use savings, the principles of consequential LCA [35–41] were applied in order to see the effects of DGS use on the total land use. Here we considered the consequences of increasing the amount of DDGS in the feed production and the reduced demand for crops as a result. The co-production factor, or DDGS yield, is 0.32 t DDGS for each tonne maize [42]. The rate of replacement of regular production by DDGS was varied among the three scenarios (see Table 2). The replaced production was then converted to a land use reduction, using the projected yield (see section 2.3.2). For the reduction of imported soy we used the Comtrade [43] database to establish the source of the agricultural production (average 2008–2012) and FAOSTAT for the local yields. The same method as described in section 2.3.2 was used to calculate the projected yield growth abroad. Despite the Netherlands and Slovenia being the main suppliers of soy to Hungary, we used the weighted average of their main suppliers: Argentina and Brazil as no noteworthy quantities of soy are grown in the Netherlands and Slovenia. While we focus on land use in Hungary, we also show possible benefits outside the region, by presenting the land use savings abroad.

2.3.4. Reducing losses in the supply chain

Food losses and food waste are often thought to be around half of the food production [44–46]. Food losses is the term used to indicate the pre-consumer losses, whereas food waste is used for losses from the consumers [47–50]. Although the gains of limiting food waste could be very large, it would involve behavioural changes by consumers. This falls outside the scope of this study, which instead focusses on the losses in agriculture and the rest of the supply chain. Reducing the losses in the chain between production and consumption of both food and fuel will help to fulfil food demand on less land. In the calculations, the difference between the baseline losses (current loss, FAOSTAT data) and the potential lower losses in the three scenarios led to a reduced demand for agricultural products; the difference is the surplus land.

The current losses are based on FAOSTAT data [30] because this is the only known source with crop and country specific data [51]. The FAO used a combination of local experts and generic loss percentages to estimate the losses during storage, distribution and processing per crop in each country, and explicitly excluding the losses in agriculture and households. The crop-specific food losses were used to calculate the share of each crop lost expressed as a percentage of the total supply. The total supply of a crop was the sum of the production, imports and stock withdrawals. This, rather than only production, was used because the losses can occur in all stages of the supply chain. The data from FAOSTAT (average 2007–2011, because more recent data was not consistently available for all crops) were used to calculate the share of crops lost in Hungary, this varies between 0.3% for rapeseed and 2.7% for potato (see Table S1 in the Supplementary Information). Where estimates for Hungary were not available for a crop, the average for the other CEE EU countries has been taken as a proxy, because these are more representative than the whole EU. The crop specific reduction is defined in each scenario.

2.3.5. Using under-utilised lands

The fourth measure is land zoning and use of under-utilised land including set-aside land, abandoned land, degraded land, marginal lands and other land that does not currently provide services [52,53]. This land can supplement the surplus land from the three other measures and be used to cultivate extra biomass for bioenergy. After the collapse of agricultural demand by the Soviet Union post-1990, the agricultural land use in Hungary has seen a decline by 11 000 km^2 (18%) [30]. As no statistics on the amount of under-utilised land exist for Hungary, this was used as a proxy. However, to avoid the use of high carbon stock lands or causing other undesired land use changes in Hungary, not all this land can be used. Part of it will have converted to forest or other land uses. The forest area in Hungary has grown by 2500 km^2 since 1990 (14%) [30]. In order to exclude these areas from the calculated potentials, we followed the observation of Schierhorn et al. [54] that carbon stocks start to increase rapidly ten years after abandonment. Therefore, this study excludes areas abandoned longer than ten years ago from the estimates of the available lands. The maximum available abandoned land is the decrease in agricultural area in the period 2003–2012, limited by the expansion of forest in that period in Hungary. This means a maximum of 4000 km^2. Availability of this area is defined per scenario in Table 2. Fallow land (2400 km^2 in 2010 [30]) is not included in this estimate because the amount of fallow land is expected to decrease rapidly as a result of the 2014–2020 reform of the European Common Agricultural Policy (CAP) [53]. The reform will see an end to payments to farmers for leaving their land fallow and thus it may not be available for bioenergy production in 2020 without risk of displacing other production.

Multiple studies [55,56] found abandoned lands to be spread evenly over the different agricultural suitability classes from IIASA. This would suggest these lands can provide an average productivity when used for maize production. However, to account for potentially lower productivity a suitability between 0.5 and 1 is included in the calculations that indicate the share of the average productivity that can be achieved.

2.3.6. Overview

Table 2 presents the assumptions at the basis of each of the scenarios. Table 3 gives the input values for each measure for each scenario and how these were derived.

2.4. Step 3 integrated analysis

In the third step, we compare the current land use with the land use for all agricultural production after application of the ILUC mitigation measures. When, after the implementation of the ILUC mitigation measures, the future land demand decreases compared to the baseline scenario, the measures help to reduce ILUC. If the land demand can be reduced even further, surplus land becomes available, that can be used for low-ILUC-risk biofuel production that does not lead to displacement. On the other hand, if the land use after the application of the measures exceeds the baseline land use, realising the biofuel target cannot be achieved without displacement of production. This would mean ILUC cannot be entirely mitigated by the measures included in this study alone, and additional actions need to be taken in order to prevent ILUC.

For the third step the measures were integrated -opposed to simply added up, because there can be synergies or trade-offs between measures. An example of this is an increased production of DDGS that has a smaller land-use impact when yields are higher. In

Table 2
Overview of the scenarios for the various measures. Table 3 shows the corresponding data for the calculations.

	Above baseline yield increase (crops)	Above baseline yield increase (livestock)	Increased chain integration	Increased chain efficiencies	Land zoning and biofuel feedstock production on abandoned lands
Baseline *Reference scenario from MIRAGE [9] with growing food, feed and fibre demand, but no additional biofuels compared to 2008.*	Crop specific projections from MIRAGE for the EU27 disaggregated to Hungary based on the current yield in Hungary as a share of the current EU27 average.	No change in the productivity per cow or hectare.[a]	None	Current losses, estimated using FAOSTAT crop-specific data. No change in the losses	Under-utilised lands will remain non-productive.
Low *Progress is low and will not rise above the current rate or the absolute minimum.*	Yields keep increasing at the average linear rate of the period 1961–2012.	Yields keep increasing at the average linear rate of the period 1961–2012.	Replacement of marginal protein source of animal feed on basis of protein content of DDGS (i.e soy imported from Argentina and Brazil is replaced). No use of stover other than current practice.	Meet the EU target of 50% food loss reduction throughout the whole chain.	Half of the abandoned land will be taken into production at 50% of the average productivity.
Medium *Knowledge in Hungary will spread, and agriculture will improve to the current or past best level in the country or CEE.*	The average yield in Hungary reaches the yield level in the current (2008–2012) best county.	The best historical productivity in Hungary.	Replacement based on feed tests in Hungary and division data to the livestock sectors from the US.	Gain the same level of chain losses (per crop) as the current best CEE country	75% of the land will be used, at 75% of the average yield.
High *Large progress in the agricultural sector. The country will catch-up with Western Europe.*	The ratio between the maximum attainable yield and currently achieved yield in Austria is applied to the maximum attainable yield in Hungary.	The highest productivity in the EU27.	Replacement on energy basis (i.e. domestic barley, maize and wheat).	Gain the same level of chain losses (per crop) as the current best EU country.	Almost all lands in the estimate can be taken into production at a productivity of 99% of the future average yield.

[a] The pasture land expansion elasticity is close to zero for the EU27 in the MIRAGE model, denoting low tendency to change.

this study the integration applied the following order:

i. The basis was the current land use for the production of the ten crops and the grassland for livestock (section 2.2).
ii. To this, the additional area for the expanded production in 2020 was added, using the projected yields (section 2.2).
iii. Then the yield was replaced by the *above baseline yield*, this reduced the land demand (section 2.3.2).
iv. Then the demand was further reduced by the implementation of *chain integration* and *chain efficiency* (section 2.3.3 and 2.3.4).
v. The resulting land demand from iv was compared to the baseline from i. in order to calculate the surplus land.
vi. The available abandoned lands were calculated (Section 2.3.5).
vii. Then the potential ethanol production on all surplus area (v and vi) was calculated, taking into account the lower yields on abandoned land (section 2.3.5), assuming all lands are used for maize production.
viii. Step iv, vi and vii were repeated to account for the extra DDGS resulting from additional ethanol production.

This resulted in a total surplus area and the potential low-ILUC-risk ethanol production. For this, an ethanol yield of 0.32 tonne ethanol for each tonne maize was applied [42]. Following Annex III of the RED [14], an energy density of 27 MJ kg^{-1} (or 21 MJ L^{-1}) was assumed.

3. Results

Table 4 presents the surplus land as a result of applying the ILUC measures. The above baseline yield development is the major source of surplus land. In all scenarios maize and wheat are more important than all the other crops combined. This can be explained by the share of these two crops in the total agricultural land use; as production increases the impact of a small yield increase is much larger. The negative amount of surplus lands for the other crops in the *low* scenario indicates that the projected yield growth in the baseline is larger than the yield growth in that scenario, and more land would be required to accommodate these crops. This is caused by a high baseline growth of rapeseed, sunflower seed and sugarbeet yields projected by MIRAGE. The additional land use for other crops is compensated by the yield growth in maize and wheat production, that are much larger. For sunflower seed, all three scenarios are below the baseline yield growth: but in the *medium* and *high* scenario the six other crops in the category *other* show a sufficient yield increase to compensate for this.

The results for the chain integration in Table 4 are presented separately for Hungary and abroad because the land-use savings abroad can not be used for low-ILUC-risk maize production in Hungary. The domestic savings in the *low* scenario are zero, because the marginal source of protein in the feed is imported soy. This means there are no domestic crops replaced and surplus land in Hungary will be zero. In the *high* scenario the savings are all domestic because the marginal source of energy in the feed is domestic barley. The *low* scenario reduces the potential effect of ILUC, by reducing the pressure on the land in Argentina and Brazil, but it does not reduce the risk of displacement within Hungary.

The reduction in maize losses contributes most to the available surplus land from increased chain efficiency in the *low* and *high* scenarios. The combination of high production and relatively large baseline losses leads to a high potential to reduce the losses. A third important aspect is the crop yield. A reduction in food losses for a low-yielding crop (e.g. rapeseed or sunflower) leads to a higher amount of surplus lands than a high yielding crop (e.g. sugarbeet or potato) as more land was needed to produce the food lost from a low yielding crop. This is an important reason for the large land use impacts of the reduction of sunflower seed losses despite its low initial losses.

The under-utilised lands here are those lands that have been previously used for agriculture and have been abandoned less than ten years ago. This combines both the use of under-utilised lands and land-zoning of potentially high carbon stock areas. In contrast to the other measures, the maize grown on these surplus lands may have a lower yield, which is why the uncertainty range applied in Laborde [9] (0.5–0.99) is applied.

Table 3
Assumptions for the calculations in each of the scenarios.

			Baseline	Low	Medium	High
Above baseline yield increase	Yields 2020 (t ha^{-1})	Maize	6.3[a]	7.1[b]	7.7[c]	9.8[d]
		Wheat	4.1	5.0	5.0	4.6
	Grazing NLU (ha^{-1})		0.24[e]	0.24[f]	0.44[g]	0.45[h]
	Cow milk productivity (m^3 y^{-1})		5.5[e]	7.2[f]	4.3[g]	7.1[h]
	Cow beef productivity (kg y^{-1})		75[e]	105[f]	100[g]	138[h]
Chain integration	Product replaced by one tonne of DDGS (t)		0[i]	0.61 soy[j]	0.38 maize; 0.31 soy; and 0.27 rapeseed[k]	1.04 barley; 0.96 wheat or 0.92 maize[l]
Chain efficiency	Losses 2020 as mass fraction (%)	Maize	2.1[m]	1.1[n]	1.2[o]	0.1[p]
		Wheat	1.8	0.9	0.6	0.3
Abandoned lands	Assumed area available (%)		0	50[q]	75	99
	Assumed productivity as share of average yield (%)		0	50	75	99

[a] The baseline yield development comes from the results of the MIRAGE model [9]. The model projects a maize yield in the EU27 in 2020 of 8.1 t ha $^{-1}$ and a wheat yield of 8.0 t ha^{-1}. As Hungary has a lower than average productivity, the baseline yield for Hungary assumes a constant ratio between the Hungarian yield and the EU27 yield between 2010 and 2020, based on the yields (2008–2012) FAOSTAT [30].

[b] The linear yield trend in Hungary of the period 1961–2012 is extended until 2020 to calculate the yield growth until 2020. The historical yield data come from FAOSTAT [30].

[c] The medium yield projection assumes for each crop the current yield of the best county in Hungary can be extrapolated to the whole country (average 2008–2012). Yield data on county level are from the Hungarian Statistics Office [31].

[d] The high yield projection considers the suitability and is calculated following the methodology of Smeets et al. [57]. Here the average maximum attainable yield for Hungary was calculated based on the IIASA Global Agro-ecological Zone (GAEZ) database [58]. In the IIASA GAEZ database, Hungary is divided into 1606 grid cells. For each crop the crop suitability is determined for rain-fed high-input agriculture in the 2020s. The suitability falls in either one of nine categories: Very high (suitability larger than 85); High (>70); Good (>55); Medium (>40); Moderate (>25); Marginal (>10); Very Marginal (>0); Not suitable (0) and water. For each grid-cell also a crop-specific agro-climatic maximum attainable yield is available. Here grid cells with a higher than average quantity of forest (22%), with more than 15% build-up area or less than 50% cultivated area are excluded in order to avoid an over-estimation of the available lands. Smeets et al. (2004) assume for each crop that production will take place on the most suitable land [57]. In 30 iterative steps, all the future production is allocated to the best available land. After allocating the baseline production to the land the average maximum attainable yield is calculated by dividing the production by the required land. Using the same methodology, the ratio between the maximum attainable yield and current yield (average FAOSTAT 2008–2012 [30]) in Austria has been assessed. This ratio is applied to the maximum attainable yield in Hungary to calculate the maximum yield for each crop. The maximum attainable yields are presented by IIASA in dry weight, whereas the FAOSTAT data (that we use for the other calculations), includes the water content of the crops. The water content of the crops presented in the GAEZ methodology document is used for the conversion [59].

[e] The amount of national livestock units (NLU) in Hungary is for cattle 0.8 and 0.0714 for sheep. In 2013 27% of cattle grazed and 67% of sheep [34]. The amount of sheep (1 190 400), cattle (969 400) and meadows and pastures (8600 km^2) were taken from FAOSTAT [30] (average 2008–2012).

[f] Low yield growth is determined by the linear yield increase in the period 1961–2012. For milk productivity this is 88 l y^{-1}, for meat 0.2 kg y^{-1}. For the density the NLU decreases by 0.02 ha^{-1} y^{-1}.

[g] The best productivity that has been registered in the past in Hungary, this was in 1983 [30]. This was the year with the most optimal combination of productivity per animal and animal density.

[h] The highest productivity in the EU is in Germany [30]. This is the country with the most optimal combination of productivity per animal and animal density.

[i] Current productivity in the Hungarian livestock sector is taken from the FAOSTAT data for the milk yield per cow (average 2008–2012) [30]. Beef productivity is determined by dividing total meat production [30] by the amount of beef cows (difference between the total amount of cows and the milk cows). For the baseline no productivity growth was assumed.

[j] The marginal source of protein (soy meal and soy oil cake) was replaced by the DDGS. DDGS contains 27% protein [60], soymeal 44% [60]. A tonne for tonne replacement of the soy production yielded 0.61 tonne soy products replaced by a tonne of DDGS. Soymeal in Hungary was imported (average 2008–2012) from The Netherlands (56%) and Slovenia (27%) that both imported from Brazil (NL: 55%; SLO: 92%) and Argentina (NL: 41%; SLO: 4%). The weighted mix was 70% from Brazil and 30% from Argentina [43]. Projected land use was 3.5 t ha^{-1} in 2020 in Brazil and 3.2 t ha^{-1} in Argentina [9]. It was assumed for each tonne of soy meal 1.29 t of soy beans was required, based on the data from Laborde [9] where 0.777 t meal is produced for each tonne of soy.

[k] American practice showed 87% of DDGS is used for cattle, 7% for pigs and 5% for poultry [61]. A feedtest by the University of Pannonia [62] showed a replacement per tonne of DDGS for cattle: 0.38t maize, 0.31t soy, 0.27t rapeseed. For pigs: 0.59t maize and 0.43t soy. For poultry 0.60t maize and 0.39t soy. In addition some minerals were replaced as well, but these have little land-use impacts.

[l] Barley (12%), wheat (21%) and maize (53%) were important feed crops for energy in Hungary (average 2007–2011) [30]. These were replaced on energy content by the use of DDGS. The energy content are 14.85 MJ kg^{-1}, 16.15 MJ kg $^{-1}$ and 16.74 MJ kg^{-1} respectively for the crops and 13.47 for the DDGS [63] -for the crops this includes a correction for the water content [59]. To calculate the *high scenario* replacement, first the lowest yielding crop (i.e. barley) is replaced by the DDGS, to the current level of use for feed in Hungary (597 kt [30]) followed by the wheat (1.1 Mt) and maize (2.8 Mt). This gave a replacement of 1.04 t barley for each tonne of DDGS. The replacement by a tonne of DDGS for wheat was 0.95t and 0.92t for maize.

[m] Current losses as reported by FAOSTAT [30]. The losses (average 2007–2011, as more recent data were not available) were divided by the total crop availability (sum of production, stock withdrawals and import). This was calculated separately for each crop.

[n] The EU has a target to cut losses in half by 2020 [64].

[o] Per crop the lowest loss that is found in a Central or Eastern European EU member (Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia) [30].

[p] Per crop the lowest loss that is found in the EU27 [30].

[q] In the uncertainty analysis of Laborde [9], the bandwidth over which the suitability of new lands is between 0.5 and 0.99, with an average value of 0.75. We use the same values here for the availability and suitability.

3.1. *Integration*

In Fig. 3 an overview is given of the land use consequences according to the disaggregation of results from MIRAGE and surplus land after implementation and integration of the four measures. As a result of overlap between some of the measures and synergies between others, the surplus lands presented in the figure differ slightly from the total in Table 4 It shows the measures generate a large amount of surplus land that can be used for energy crop production, even in the *low* scenario.

Table 5 presents the amount of low-ILUC-risk ethanol that can be produced from the surplus land in Hungary. The land use to accommodate the ten most important crops in Hungary can decrease compared to the baseline and even compared to the present. This leaves room for additional production of low-ILUC-risk maize for ethanol, ranging from 42 to 187 PJ of maize ethanol.

4. Monitoring ILUC and ILUC mitigation measures

Monitoring the effectiveness of the measures is required to

Table 4
Surplus land (km^2) as a result of the four measures in the *low*, *medium* and *high* scenario.

		Low	Medium	High
Above baseline yield increases (km^2)	Maize	1750	1520	4670
	Wheat	2060	2330	1180
	Other crops	−90	1070	450
	Livestock	1630	3870	5170
	Subtotal	5340	8790	11 480
Chain integration (km^2)	Domestic	0	90	170
	(Abroad)[a]	130	50	0
Chain efficiency (km^2)	Maize	140	120	260
	Wheat	110	140	190
	Other crops	60	50	90
	Subtotal	300	320	540
Under-utilised land (km^2)		2010	3010	3970
Total (km^2)		7650	12 210	16 160

[a] Not included in the totals.

ensure the risk of ILUC is indeed minimised. Tables 6 and 7 present the parameters that are ideally monitored in order to assess the effectiveness of general land use (change) and specific ILUC mitigation policies, respectively. The indicators in Table 6 are related to agricultural production and land use and can help to determine whether the policy measures are effective to limit unwanted land use change. The parameters presented in Table 7 can help to assess the specific ILUC mitigation measures. The desired frequency and spatial scale are suggested for each parameter, as well as the current availability and quality of the data. The parameters listed in the tables are explained in more detail below.

More accurate measurements of the land use can help to keep track of land expansion within the region in order to prevent large-scale expansion on high carbon stock lands (or other environmentally sensitive areas). The land use and land use change can be monitored with a combination of field measurements and usage of satellite and other remote sensing data. In addition, land that is abandoned or set-aside according to the statistics can be used in practice for extensive uses such as livestock herding. A yearly update of the data ensures these are up-to-date and helps to better track land use expansion.

The production volume of the major crops needs to be monitored in order to establish whether the projections from the model are accurate. Too low production can simply be a consequence of decreasing worldwide demand; or it can be a precursor of increased imports or reduced exports and thereby increased risk of undesired land use change as the extra production needs to take place outside Hungary. Too high production could indicate increasing demand, not accounted for in the model. This risks unwanted land expansion on e.g. high carbon stock lands in Hungary. Agricultural production is already well monitored and analysis by Kim and Dale shows FAOSTAT and national statistics differ less than one percent in most cases [51].

Large price increases in Hungary can indicate too low production to cover demand, and thus precede land-use expansion in order to meet demand. World market prices are very well reported and even daily fluctuations can be observed.

Data on many of the parameters are already reported by FAOSTAT [30], EUROSTAT [65] or the Hungarian Central Statistics Office [31]. To monitor the average yield developments in Hungary, this is sufficient. But more data on the variation in yields (e.g. yield ranges on national, provincial and county level and yields for different producers such as large vs. smallholder farms) can identify areas that need additional attention for increasing yields. The baseline yield increase can be set as a threshold value; when the actual yield is below this value, it denotes no low-ILUC-risk biomass production can be achieved from this measure.

Measures to increase the yields include increased mechanisation, modernizing farm equipment and improved fertiliser use. FAOSTAT [30] and the World Bank [25] already keep records of investments, mechanisation and fertiliser use in agriculture. These data are often not up-to-date and only available for selected countries. However, if collected yearly, they could be a proxy for the yield improvements. Monitoring agrochemicals use and supplication for different crops will help to identify areas of improvements. Government support for agriculture can be derived from the OECD [68].

The first step for monitoring crop losses in Hungary would be to establish the current losses, as no accurate crop-specific data is available at the moment. FAOSTAT [30] has some data on losses, but not thoroughly. With continuous monitoring of the losses in the supply chain, it is possible to assess if the reduction matches the target.

The development of abandoned lands needs to be monitored to see how much land is available and to see if it is taken into production. Spatially explicit data would ideally be used for this.

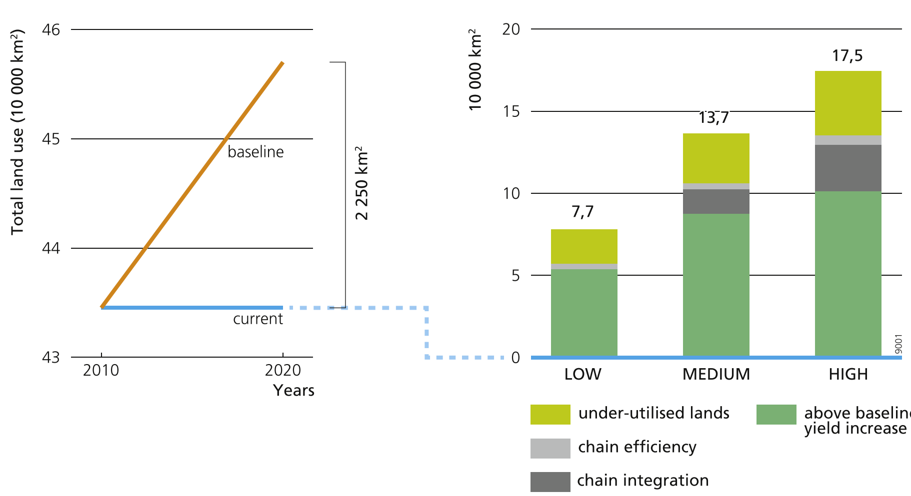

Fig. 3. Comparison of land use change projected in MIRAGE (Panel A) with land generated from ILUC mitigation measures (Panel B). Panel A shows the current and projected (baseline and biofuels target) land use in Hungary for the cultivation of crops according to a disaggregation of results from MIRAGE. Panel B shows the potential of each measure to overcome the gap between the target and current land use.

Table 5
Low-ILUC-risk maize production in Hungary on the surplus lands and the potential bioethanol production in 2020 at a yield of 0.32 tonne ethanol for each tonne of maize.

	Low-ILUC-risk maize production (Mt y^{-1})	Bioethanol production (PJ y^{-1})	Share Hungarian road transport energy 2020 (%)
Low	4.8	0.42	19%
Medium	9.5	0.82	37%
High	22	0.187	83%

Table 6
Main parameters to be monitored in Hungary to ascertain no unwanted land use change takes place.

Parameter	Purpose of monitoring	Desired frequency	Desired spatial scale	Available data	
				Sources	Quality
Land use	Is any land use expansion taking place? Are under-utilised lands taken into production? How much under-utilised land is still available? Are forests, biodiverse grasslands or other important ecosystem service areas converted to crop production? Where are the important carbon stocks?	Yearly	Spatially explicit	[30,31,65]	±
Production volume	Production developing as projected?	Yearly (at a five year average)	Country level	[30,31,65]	++
Trade balance	No major increase in imports of agricultural products or processed goods? Or decrease in exports? Decrease in soy and other feed imports?	Yearly (at a five year average)	Country level	[30,43,66,67]	++
Agricultural prices	Absolute price stability? Relative price stability?	Seasonal	Country level	[30,65,68], Nasdaq, euronext	++

Current statistics are not sufficient as these do not include previous land-use or when conversion took place. Furthermore, comparison of satellite data with official data in Eastern Europe -especially on sub-national level-showed a difference between the two [69]. Using spatially explicit data can also be combined with the land suitability (e.g. IIASA data [58]) to monitor the potential yield on these lands.

Ethanol production from Hungarian-grown maize can take place in many countries. For DDGS a similar situation occurs, the DDGS can be used in Hungary and replace Hungarian agricultural production, but this is not certain. For monitoring we suggest to record the share of each feed crop in the Hungarian feed mix, this makes it possible to establish how much feed is replaced by the use of DDGS and where this feed originated. As the animal feed mix is continuously changing, a yearly overview of feed use is needed.

5. Discussion and conclusions

A key measure to minimise the risk of ILUC is to increase agricultural yields. By investing in productivity improvements and closing the yield gap, land can be released from food and feed production and then be used to produce low-ILUC-risk biofuel. But

Table 7
Parameters to assess the effectiveness of the ILUC mitigation measures.

Parameter	Purpose of monitoring	Desired frequency	Desired spatial scale	Available data	
				Source	Quality
Yields	Is the yield increase in the different crops as high as desired?	Yearly (at a five year average)	Country level (incl. ranges)	[30,31,65]	+ Yields are reported, but no spatial explicit data on farm level is available
Investments	Are investments in machinery increasing?	Yearly	Country level	[25,30]	– outdated and no specification what type of investments
Fertiliser use	Is fertiliser use increasing? Is it at the level of the rest of Europe? Is it used in bulk or in precision farming?	Yearly	Country level (incl. ranges), crop-specific	[25,30,68]	± Outdated and only country averages
Pesticide use	Is pesticide use increasing? Is it at the level of other European countries?	Yearly	Country level	[30]	± Outdated and only country averages
Chain losses	How high are the losses? Are they reducing as much as expected in the scenarios?	Continuously	Crop specific at country level	[30]	– Very uncertain for current losses and not up to date.
Development of under-utilised lands	How much abandoned land exists and where? What quantity is being taken into production and for what? Where is reforestation taking place and what are the carbon stocks? Where are abandoned areas used extensively and for what purpose?	Yearly	Spatially explicit	[30,31]	–– Current under-utilised lands not monitored. No information on location and quality
Quality of degraded lands	Is crop production possible on these lands? What yields can be achieved on the degraded lands?	Yearly	Spatially explicit	[58]	– Only the average quality of the lands, not specific forany of the forms of under-utilised land.
Quantity of degraded lands	How much degraded land is available and where? How much is taken into production?	Yearly	Spatially explicit		–– No information available
Feed use	How much DDGS is included in the feed? What and how much does it replace?	Yearly	Feed specific country level		– No macro data available

also other measures exist that reduce the pressure on agricultural land and thereby minimise the risk of additional production leading to displacement. Examples are efficiency gains in the supply chain in the form of reducing losses in production, transportation and processing; efficient use of co-products from biofuels; and bringing currently under-utilised lands, which do not conflict with nature conservation efforts and other essential uses or functions, into production. Using a case study of maize for ethanol production in Hungary, we demonstrate that these four measures can minimise the risk of ILUC. Because the combination of the four measures creates a large surplus area in addition to covering the slightly increased future food production, there is room for expansion of biofuel feedstock production in Hungary. As this biofuel feedstock can be produced on surplus agricultural area, the additional production has a low-risk of displacing other crops to high carbon stock lands in Hungary or abroad. Using this surplus land to grow maize for ethanol could provide 1–6.6 10^6 m^3 ethanol and replace the equivalent of 22–138 PJ gasoline per year. This equals 10%–60% of the projected energy use of the Hungarian road transport sector in 2020 [70].

The relatively large impact of increasing yields on the total low-ILUC-risk potential (55%–90%) suggests that other regions with a high yield gap may also be able to provide significant amounts of low-ILUC-risk biofuels. However, this also requires a low projected food demand increase (as Hungary has). Other regions in Central and Eastern Europe such as Poland, Romania and Ukraine share these characteristics [9,71]. For example, for Lublin province in Poland, it was already shown that abandoned lands and yield increases can account for three quarters of the surplus land to produce all projected second generation ethanol for Poland [28]. Large yield gaps are also found in Asia and Africa, but food production increases are likely to reduce the low-ILUC-risk potential there [9,71].

Developing the low-ILUC-risk potential requires a large effort in modernizing and sustainably intensifying the entire agricultural sector. Although the yield gap in Hungary is large (4.2 t ha^{-1} for maize), the projected baseline yield increases until 2020 are low (0.1 t ha^{-1} for maize). Therefore a significant increase to the yields (up to 3.6 t ha^{-1} for maize) is considered feasible (for a more detailed discussion on this, see the Supplementary Information). However, monitoring the developments in the Hungarian agricultural sector is necessary in order to ascertain that the incentives to stimulate these efforts have sufficient effect on increasing productivity and preventing unwanted land use change. Slower progress than expected reduces the low-ILUC-risk biofuel potential and can be a warning signal for curbing any further expansion of biofuel feedstock production. This makes the biofuel production dependent on progress in agricultural productivity, which can help prevent biofuel production to grow above the low-ILUC-risk potentials.

An important limitation to this study is that it did not include the GHG emission effects associated with the implementation of the ILUC mitigation measures. Increasing yields through more mechanisation and fertiliser use may increase the overall GHG emissions of crop production. This can limit the GHG emission gains from preventing ILUC. However, the combined effect of higher productivity and decreased inputs per unit of agricultural production may result in lower GHG emissions per unit biomass. Although we did not assess this for our study, the analysis from Gerssen-Gondelach et al. [72] showed sustainable intensification for ILUC mitigation can lower the GHG emission footprint of the entire agricultural sector in Lublin. However, the emission balance largely depends on how intensification is implemented and what crop is grown for biofuels. Key determining factors include fertiliser management, application of tillage and the level of soil organic carbon (SOC). Given Gerssen-Gondelach et al. [72] assessed miscanthus, which can support SOC sequestration and therefore has low or negative emissions overall. It is unclear how this translates to the GHG emission balance of ethanol from maize. Therefore, more research is needed to better understand the effect of intensification in other settings, such as this case study.

The findings of this study emphasise that developing the biofuel potential of Hungary in a sustainable manner needs a focus on the agricultural sector as a whole, not only on the production of the biofuel feedstock. This is because such a holistic approach to the land use for food, feed, fibre and fuel production addresses the interlinkages between the biofuel and agricultural sectors that actually can cause ILUC. Thereby, the ILUC-risk is mitigated at the root cause of the problem. This is an improvement over the much-discussed ILUC penalty approach, which falls short in terms of applying uniform penalties independent of how and where the feedstock is produced and has many uncertainties in the quantification of the actual factors.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2017.02.006.

References

[1] T. Searchinger, R. Heimlich, R.A.R. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, T.-H. Yu, Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change, Science 319 (80) (2008) 1238–1240, http://dx.doi.org/10.1126/science.1151861.

[2] T. Hertel, W. Tyner, Market-mediated environmental impacts of biofuels, Glob. Food Sec 2 (2013) 131–137, http://dx.doi.org/10.1016/j.gfs.2013.05.003.

[3] W.E. Tyner, F. Taheripour, Q. Zhuang, Land Use Changes and Consequent CO2 Emissions Due to US Corn Ethanol Production: a Comprehensive Analysis, Department of Agricultural Economics, Purdue University, 2010. https://greet.es.anl.gov/files/8vdox40k (Accessed 31 January 2014).

[4] D.M. Lapola, R. Schaldach, J. Alcamo, A. Bondeau, J. Koch, C. Koelking, J. a Priess, Indirect land-use changes can overcome carbon savings from biofuels in Brazil, Proc. Natl. Acad. Sci. 107 (2010) 3388–3393, http://dx.doi.org/10.1073/pnas.0907318107.

[5] A.G. Prins, E. Stehfest, K. Overmars, J.P.M. Ros, Are Models Suitable for Determining Iluc Factors?, Netherlands Environmental Assessment Agency, Bilthoven, 2010. http://www.pbl.nl/sites/default/files/cms/publicaties/500143006.pdf (Accessed 11 March 2015).

[6] F. Taheripour, W.E. Tyner, Induced land use emissions due to first and second generation biofuels and uncertainty in land use emission factors, Econ. Res. Int. (2013) 1–12. http://www.hindawi.com/journals/econ/2013/315787/abs/ (Accessed 31 January 2014).

[7] US EPA Transportation Office Air Quality Standards Division, Draft Regulatory Impact Analysis: Changes to Renewable Fuel Standard Program, 2009. http://www.epa.gov/otaq/renewablefuels/420d09001.pdf (Accessed 31 January 2015).

[8] California Air Resources Board Proposed Regulation to Implement the Low Carbon Fuel Standard Volume I, 2009, https://www.arb.ca.gov/regact/2009/lcfs09/lcfsisor1.pdf (Accessed 31 January 2015).

[9] D. Laborde, Assessing the Land Use Change Consequences of European Biofuel Policies, International Food Policy Research Institute, Washington DC, 2011. http://trade.ec.europa.eu/doclib/docs/2011/october/tradoc_148289.pdf (Accessed 2 June 2014).

[10] P. Al-Riffai, B. Dimaranan, D. Laborde, Global Trade and Environmental Impact

Study of the Eu Biofuels Mandate, International Food Policy Research Institute, Washington DC, 2010. http://trade.ec.europa.eu/doclib/html/145954.htm (Accessed 2 June 2014).

[11] B. Wicke, P. Verweij, H. van Meijl, D.P. van Vuuren, A.P.C. Faaij, Indirect land use change: review of existing models and strategies for mitigation, Biofuels 3 (2012) 87–100, http://dx.doi.org/10.4155/bfs.11.154.

[12] S. Ahlgren, L. Di Lucia, Indirect land use changes of biofuel production - a review of modelling efforts and policy developments in the European Union, Biotechnol. Biofuels 7 (2014) 35, http://dx.doi.org/10.1186/1754-6834-7-35.

[13] U.R. Fritsche, K. Hennenberg, K. Hünecke, The "iLUC factor" as a Means to Hedge Risks of GHG Emissions from Indirect Land Use Change, 2010. Working Paper, http://www.oeko.de/oekodoc/1030/2010-082-en.pdf.

[14] The European Parliament and the Council of the European Union, Renewable Energy Directive 2009/28/EC, 2009.

[15] The European Parliament and the Council of the European Union, Amending Directive 98/70/EC Relating to the Quality of Petrol and Diesel Fuels and Amending Directive 2009/28/EC on the Promotion of the Use of Energy from Renewable Sources, the European Parliament and the Council of the European Union, 2015. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ. L: 2015:239:FULL.

[16] R.J. Plevin, J. Beckman, A.A. Golub, J. Witcover, M. O'Hare, Carbon accounting and economic model uncertainty of emissions from biofuels-induced land use change, Environ. Sci. Technol. (2015) 2656–2664, http://dx.doi.org/10.1021/es505481d.

[17] R.J. Plevin, A.D. Jones, M.S. Torn, H.K. Gibbs, M. O'Hare, A.D. Jones, M.S. Torn, H.K. Gibbs, Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may Be much greater than previously estimated, Environ. Sci. Technol. 44 (2010) 8015–8021, http://dx.doi.org/10.1021/es101946t.

[18] B. Wicke, F. van der Hilst, V. Daioglou, M. Banse, T. Beringer, S. Gerssen-Gondelach, S. Heijnen, D. Karssenberg, D. Laborde, M. Lippe, H. van Meijl, A. Nassar, J. Powell, A.G. Prins, S.N.K. Rose, E.M.W. Smeets, E. Stehfest, W.E. Tyner, J.A. Verstegen, H. Valin, D.P. van Vuuren, S. Yeh, A.P.C. Faaij, Model collaboration for the improved assessment of biomass supply, demand, and impacts, GCB Bioenergy 7 (2015) 422–437, http://dx.doi.org/10.1111/gcbb.12176.

[19] M. Finkbeiner, Indirect land use change – help beyond the hype? Biomass Bioenergy 62 (2014) 218–221, http://dx.doi.org/10.1016/j.biombioe.2014.01.024.

[20] J.H. Schmidt, B.P. Weidema, M. Brandão, A framework for modelling indirect land use changes in Life Cycle Assessment, J. Clean. Prod. 99 (2015) 230–238, http://dx.doi.org/10.1016/j.jclepro.2015.03.013.

[21] M. de Wit, A. Faaij, European biomass resource potential and costs, Biomass Bioenergy 34 (2010) 188–202, http://dx.doi.org/10.1016/j.biombioe.2009.07.011.

[22] M. de Wit, M. Londo, A. Faaij, Productivity developments in European agriculture: relations to and opportunities for biomass production, Renew. Sustain. Energy Rev. 15 (2011) 2397–2412, http://dx.doi.org/10.1016/j.rser.2011.02.022.

[23] E. Smeets, A. Faaij, I. Lewandowski, W. Turkenburg, A bottom-up assessment and review of global bio-energy potentials to 2050, Prog, Energy Combust. Sci. 33 (2007) 56–106, http://dx.doi.org/10.1016/j.pecs.2006.08.001.

[24] F. van der Hilst, J.A. Verstegen, T. Zheliezna, O. Drozdova, A.P.C. Faaij, Integrated spatiotemporal modelling of bioenergy production potentials, agricultural land use, and related GHG balances; demonstrated for Ukraine, Biofuels, Bioprod, Biorefining 8 (2014) 391–411, http://dx.doi.org/10.1002/bbb.1471.

[25] World Bank, Indicators Agriculture & Rural Development, 2015. http://data.worldbank.org/indicator (Accessed 31 January 2015).

[26] N. Kohlheb, F. Krausmann, Land use change, biomass production and HANPP: the case of Hungary 1961–2005, Ecol. Econ. 69 (2009) 292–300, http://dx.doi.org/10.1016/j.ecolecon.2009.07.010.

[27] M.L.J. Brinkman, B. Wicke, S.J. Gerssen-Gondelach, C. van der Laan, A.P.C. Faaij, Methodology for Assessing and Quantifying ILUC Prevention Options, Copernicus Institute, Utrecht University, Utrecht, the Netherlands, 2015. http://www.uu.nl/en/files/20150106-iluc-methodology-reportpdf.

[28] S.J. Gerssen-Gondelach, B. Wicke, M. Borzęcka-Walker, R. Pudełko, A.P.C. Faaij, Bioethanol potential from miscanthus with low ILUC risk in the province of Lublin, Poland, GCB Bioenergy 8 (2016) 909–924, http://dx.doi.org/10.1111/gcbb.12306.

[29] C. Van der Laan, B. Wicke, P.A. Verweij, A.P.C. Faaij, Mitigation of unwanted direct and indirect land-use change - an integrated approach illustrated for palm oil, pulpwood, rubber and rice production in North and East Kalimantan, Indonesia, GCB Bioenergy 9 (2017) 429–444, http://dx.doi.org/10.1111/gcbb.12353.

[30] Food and Agriculture Organisation, FAOSTAT, 2015. http://faostat3.fao.org/ (Accessed 18 December 2015).

[31] KSH, Hungarian Central Statistics Office. http://www.ksh.hu/, 2015 (Accessed 31 January 2015).

[32] M.L.J. Brinkman, B. Wicke, A.P.C. Faaij, ILUC Prevention Strategies for Sustainable Biofuels ILUC Prevention Strategies for Sustainable Biofuels Case Study on the Bioethanol Production Potential with Low-ILUC-risk from Hungarian Corn,Copernicus Institute, Utrecht University, Utrecht, 2015.

[33] S. Gerssen-Gondelach, B. Wicke, A. Faaij, Assessment of driving factors for yield and productivity developments in crop and cattle production as key to increasing sustainable biomass potentials, Food Energy Secur 4 (2015) 36–75, http://dx.doi.org/10.1002/fes3.53.

[34] KSH, Agricultural Census 2013, 2014. https://www.ksh.hu/agricultural_census (Accessed 23 July 2015).

[35] H. Baumann, A. Tilman, The Hitchhikers Guide to LCA, Studentlitteratur AB, Lund, 2004.

[36] G. Finnveden, M.Z. Hauschild, T. Ekvall, J. Guinée, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington, S. Suh, Recent developments in life cycle assessment, J. Environ. Manage 91 (2009) 1–21, http://dx.doi.org/10.1016/j.jenvman.2009.06.018.

[37] T. Ekvall, B.P. Weidema, System boundaries and input data in consequential life cycle inventory analysis, Int. J. Life Cycle Assess. 9 (2004) 161–171, http://dx.doi.org/10.1007/BF02994190.

[38] M. Brander, R. Tipper, C. Hutchinson, G. Davis, Consequential and attributional approaches to LCA: a guide to policy makers with specific reference to greenhouse gas LCA of biofuels, Tech. Pap. (2009) 1–14. TP-090403-A, http://ecometrica.com/assets/approachesto_LCA3_technical.pdf (Accessed 2 June 2014).

[39] S. Unnasch, B. Riffel, S. Sanchez, L. Waterland, Review of transportation fuel life cycle analysis CRC report No. E-88, Coord. Res. Counc. (2011). http://www.crcao.com/reports/recentstudies2011/E-88/E-88. Report v8 Final 2011.03.02.pdf (Accessed 1 September 2013).

[40] J. Reinhard, R. Zah, Consequential life cycle assessment of the environmental impacts of an increased rapemethylester (RME) production in Switzerland, Biomass Bioenergy 35 (2011) 2361–2373, http://dx.doi.org/10.1016/j.biombioe.2010.12.011.

[41] K. Südekum, G. Flachowsky, F. Kalscheur, Comment on "Assessing the land use change consequences of European biofuel policies" by David Laborde, Biokraftstoffverband (2013).

[42] S. Mueller, J. Kwik, 2012 corn ethanol: emerging plant energy and environmental technologies, Energy Resour. Cent. Univ. Chic. (2013) 26. http://ethanolrfa.3cdn.net/fe5f4b7a4bdbc12101_2gm6bejk4.pdf (Accessed 23 April 2014).

[43] UN Comtrade, (2014). http://comtrade.un.org/data/(Accessed 27 May 2014).

[44] J. Parfitt, M. Barthel, S. Macnaughton, Food waste within food supply chains: quantification and potential for change to 2050, Philos. Trans. R. Soc. Lond. B. Biol. Sci. 365 (2010) 3065–3081, http://dx.doi.org/10.1098/rstb.2010.0126.

[45] E. Papargyropoulou, R. Lozano, J.K. Steinberger, N. Wright, Z. Bin Ujang, The food waste hierarchy as a framework for the management of food surplus and food waste, J. Clean. Prod. 76 (2014) 106–115, http://dx.doi.org/10.1016/j.jclepro.2014.04.020.

[46] J. Lundqvist, C. de Fraiture, D. Molden, Saving Water: from Field to Fork - Curbing Losses and Wastage in the Food Chain, 2008. http://www.unwater.org/downloads/Paper_13_Field_to_Fork.pdf (Accessed 23 July 2015).

[47] J. Gustavsson, C. Cederberg, U. Sonesson, Global Food Losses and Food Waste, Swedish Institute Food Biotechnol, 2011. http://www.fao.org/docrep/014/mb060e/mb060e.pdf (Accessed 1 September 2014).

[48] J. Gustavsson, C. Cederberg, U. Sonesson, A. Emanuelsson, The Methodology of the FAO Study: "Global Food Losses and Food Waste - Extent, Causes and Prevention " - FAO, 2011, Swedish Inst. Food Biotechnol, 2013. http://www.sik.se/archive/pdf-filer-katalog/SR857.pdf (Accessed 1 September 2014).

[49] V. Smil, Improving efficiency and reducing waste in our food system, Environ. Sci. 1 (2004) 17–26, http://dx.doi.org/10.1076/evms.1.1.17.23766.

[50] L. Secondi, L. Principato, T. Laureti, Household food waste behaviour in EU-27 countries: a multilevel analysis, Food Policy 56 (2015) 25–40, http://dx.doi.org/10.1016/j.foodpol.2015.07.007.

[51] S. Kim, B.E. Dale, Global potential bioethanol production from wasted crops and crop residues, Biomass Bioenergy 26 (2004) 361–375, http://dx.doi.org/10.1016/j.biombioe.2003.08.002.

[52] J. van de Staaij, D. Peters, B. Dehue, S. Meyer, V. Schueler, G. Toop, V. Junquera, L. Máthé, Low Indirect Impact Biofuel (LIIB) Methodology - Version Zero, Eofys, WWF, 2012, p. 56. http://www.ecofys.com/files/files/12-09-03-liib-methodology-version-0-july-2012.pdf (Accessed 10 May 2013).

[53] B. Allen, B. Kretschmer, D. Baldock, H. Menadue, S. Nanni, G. Tucker, Space for Energy Crops – Assessing the Potential Contribution to Europe's Energy Future, 2014. http://www.ieep.eu/assets/1392/IEEP_2014_Space_for_Energy_Crops.pdf (Accessed 9 September 2015).

[54] F. Schierhorn, D. Müller, T. Beringer, A.V. Prishchepov, T. Kuemmerle, A. Balmann, Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus, Glob. Biogeochem. Cycles 27 (2013) 1175–1185, http://dx.doi.org/10.1002/2013GB004654.

[55] P. Griffiths, D. Müller, T. Kuemmerle, P. Hostert, Agricultural land change in the Carpathian ecoregion after the breakdown of socialism and expansion of the European Union, Environ. Res. Lett. 8 (2013) 45024, http://dx.doi.org/10.1088/1748-9326/8/4/045024.

[56] C. Alcantara, T. Kuemmerle, M. Baumann, E.V. Bragina, P. Griffiths, P. Hostert, J. Knorn, D. Müller, A.V. Prishchepov, F. Schierhorn, A. Sieber, V.C. Radeloff, Mapping the extent of abandoned farmland in Central and Eastern Europe using MODIS time series satellite data, Environ. Res. Lett. 8 (2013) 35035, http://dx.doi.org/10.1088/1748-9326/8/3/035035.

[57] E. Smeets, A. Faaij, I. Lewandowski, A Quickscan of Global Bio-energy Potentials to 2050 an Analysis of the Regional Availability of Biomass Resources for Export in Relation to the Underlying Factors, 2004. http://www.bioenergytrade.org/downloads/smeetsglobalquickscan2050.pdf (Accessed 6

June 2014).
[58] IIASA, FAO, Global Agro-ecological Zones (GAEZ v3.0), 2012. http://www.gaez.iiasa.ac.at/ (Accessed 1 October 2014).
[59] IIASA, Global, Agro-ecological Zones Model Documentation, 2009. http://www.gaez.iiasa.ac.at/docs/GAEZ_Model_Documentation.pdf (Accessed 23 October 2014).
[60] W. Lywood, J. Pinkney, An outlook on EU biofuel production and its implications for the animal feed industry, in: H. Makkar (Ed.), Biofuel Co-products as Livest. Feed - Oppor. Challenges, FAO - Food and Agriculture Organisation, Rome, 2012, pp. 13–34.
[61] L.A. Hoffman, A.J. Baker, Estimating the Substitution of Distillers' Grains for Corn and Soybean Meal in the US Feed Complex, USDA, 2011, p. 62. http://ethanol.org/pdf/contentmgmt/USDA_report_on_subbing_DDGS_for_Corn_and_Soybean_Meal_in_the_US-1.pdf (Accessed 2 June 2014).
[62] University of Pannonia, Usability of Corn Dried Distillers Grains with Solubles (DDGS) in the Feeding of Ruminants, Swine and Poultry, 2011, p. 27. http://www.pannoniagold.com/wp-content/uploads/usability_corn_ddgs_pig_bull_dairy_poultry.pdf (Accessed 6 February 2014).
[63] J. Noblet, H. Fortune, C. Dupire, S. Dubois, Digestible, metabolizable and net energy values of 13 feedstuffs for growing pigs: effect of energy system, Anim. Feed Sci. Technol. 42 (1993) 131–149, http://dx.doi.org/10.1016/0377-8401(93)90029-J.
[64] European Commission, Roadmap to a Resource Efficient Europe, 2011.
[65] Eurostat, Eurostat, (2015). http://epp.eurostat.ec.europa.eu/(Accessed 31 January 2015).
[66] World Trade Organisation, WTO Statistics, 2015. https://www.wto.org/english/res_e/statis_e/merch_trade_stat_e.htm.
[67] International Monetary Fund, IMF Data, 2015. http://www.imf.org/en/data.
[68] Organisation for Economic Cooperation and Development, OECD Data, 2015. https://data.oecd.org.
[69] P.V. Potapov, S.A. Turubanova, A. Tyukavina, A.M. Krylov, J.L. McCarty, V.C. Radeloff, M.C. Hansen, Eastern Europe's forest cover dynamics from 1985 to 2012 quantified from the full Landsat archive, Remote Sens. Environ. 159 (2015) 28–43, http://dx.doi.org/10.1016/j.rse.2014.11.027.
[70] Hungary, National, Renewable Energy Action Plan (NREAP), 2010. http://ec.europa.eu/energy/sites/ener/files/documents/dir_2009_0028_action_plan_hungary.zip (Accessed 3 December 2014).
[71] Global Yield Gap and Water Productivity Atlas, (n.d.). http://www.yieldgap.org/(Accessed 11 January 2017).
[72] S.J. Gerssen-Gondelach, B. Wicke, A.P.C. Faaij, GHG emissions and other environmental impacts of indirect land use change mitigation, GCB Bioenergy (2016) 192–226, http://dx.doi.org/10.1111/gcbb.12394.